

X-RAY TIMING OBSERVATIONS AND GRAVITATIONAL PHYSICS

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Photon-rich X-ray observations on bright compact galactic sources will make it possible to detect many fast processes that may occur in these systems on millisecond and submillisecond timescales. Many of these processes are of direct relevance to gravitational physics because they arise in regions of strong gravity near neutron stars and black holes where the dynamical timescales for compact objects of stellar mass are milliseconds. To date, such observations have been limited by the detector area and telemetry rates available. However, instruments such as the proposed X-ray Large Array (XLA) would achieve collecting areas of about 100 m². This instrument has been described elsewhere (Wood and Michelson 1988) and was the subject of a recent prephase A feasibility study at Marshall Space Flight Center. Observations with an XLA class instrument will directly impact five primary areas of astrophysics research: the attempt to detect gravitational radiation, the study of black holes, the physics of mass accretion onto compact objects, the structure of neutron stars and nuclear matter, and the characterization of dark matter in the universe. In this talk we will focus on those observations that are most directly relevant to gravitational physics: the search for millisecond X-ray pulsars that are potential sources of continuous gravitational radiation; and the use of X-ray timing observations to probe the physical conditions in extreme relativistic regions of space near black holes, both stellar-sized and supermassive ($>10^6$ solar masses). These observations can be used to find answers to gravitational physics questions such as the following.

- Are rapidly-spinning neutron stars subject to relativistic instabilities that lead to the emission of gravitational radiation?
- Do marginally stable orbits exist around neutron stars?
- Do accreting neutron stars in binaries evolve primarily by orbit decay associated with gravitational radiation emission?
- Are light curves of predicted binary millisecond X-ray pulsars modified by gravitational lensing?
- What are the submillisecond temporal characteristics of galactic black holes?
- What are the angular diameters of X-ray emitting regions around compact objects in active galactic nuclei?
- What is the extent of X-ray emission associated with halos of clusters of galaxies, and does it imply the presence of dark matter?

The direct detection of gravitational radiation is perhaps the primary goal of experimental gravitational physics. While emission of such radiation has been inferred from radio observations of a neutron star binary system, efforts to directly detect gravity waves have not yet succeeded. The predicted sources of gravitational

radiation may be broadly subdivided according to whether emission is produced in a short burst, as a stochastic background, or as a continuous wave at a single frequency. Continuous wave emission is of interest in connection with bright accreting neutron stars in binaries.

Rapidly rotating neutron stars become secularly unstable when subjected to viscous dissipative forces or gravitational radiation reaction (Chandrasekhar 1970, Friedman and Schutz 1978). Modes that grow via gravitational radiation reaction are damped by viscosity and vice versa. This process, often referred to as the Chandrasekhar-Friedman-Schutz (CFS) instability, was originally considered applicable to a situation in which a neutron star is born with a spin period near 1 ms and then deaccelerated by the torque associated with gravitational radiation. In a reference frame rotating with the star, the CFS mode manifests itself as a nonaxisymmetric deformation of the star (with mode number $m = 3$ or 4) that counter-rotates. For the CFS mechanism to deliver CW gravitational radiation over a prolonged time, the angular momentum radiated away must be replenished. Nature provides an appropriate situation when a neutron star with a weak magnetic field accretes material from a binary companion. In an accretion environment, the neutron star need not start with a short period. Accretion provides a spin-up torque that can first drive the neutron star into the unstable regime and then keep it there, ultimately reaching an equilibrium in which angular momentum lost by gravitational radiation equals that gained from accretion. This scenario was recently described theoretically by Wagoner (1984). The model requires that the star have a weak magnetic field in order that the accretion disk extend to the stellar surface and deliver angular momentum continuously.

In equilibrium, gravitational radiation is emitted at a frequency f associated with the pattern speed of the nonaxisymmetric distortion as seen in the observer's frame. This frequency depends on details of the neutron star's structure and its viscosity. It is predicted to lie in the range $200 \text{ Hz} < f < 800 \text{ Hz}$, below the rotation frequency of the star.

X-ray radiation is emitted as a consequence of the accretion process. Indeed, most of the gravitational energy of the accreting matter is released in X-rays, while most of the angular momentum is removed by gravitational radiation. Because of the nonaxisymmetric distortion of the star, the X-ray flux is expected to be weakly modulated at the same frequency as the gravitational radiation. This situation constitutes a new kind of binary X-ray pulsar that has never been detected, probably because the frequency is very high, the level of modulation is very low, and the pulsar is in a binary system. All of these conditions make detection with a small aperture detector very difficult. An XLA class instrument enormously improves the detection probability.

Detection in either the X-ray or the gravity wave channel facilitates the search in the other channel. One could discover the pulsar in X-rays and use knowledge of the frequency to search for the gravity wave signal. Detection of the X-ray pulsations by itself would be significant, settling some major issues in astrophysics. The period of the X-ray modulation would give information about the equation of state of matter at high densities and information about the viscosity. The theory of the X-ray pulsation mechanism in these systems could be tested. Dual-channel detection of the source in both X-rays and gravity waves would provide two measures of the neutron star distortion and would lead to a variety of new observational tests, *e.g.*, tracking the angular momentum as it is added by accretion and removed by gravitational radiation.

We now turn to consideration of how X-ray timing applies to the study of black holes. These gravitationally collapsed objects are an allowed endpoint of evolution of massive bodies in General Relativity. Specific astrophysical candidates have been identified in two very different mass ranges: stellar candidates such as Cygnus X-1 and active galactic nuclei (AGN), with masses from about 10^5 to perhaps more than 10^7 solar masses. Black holes play a fundamental role in astrophysics, in large part because accretion onto black holes is thought to be the energy release mechanism that powers the quasars and other AGNs.

X-ray and even gamma-ray observations have contributed enormously to the identification and study of black hole candidates, mainly because it is in these high-energy channels that the sources are highly luminous and well-isolated. Since the radiation emitted by accretion can vary on the relevant dynamical timescales, fast timing and time-resolved spectroscopy are crucial, just as for neutron stars. However, we must acknowledge that no high-energy observations by themselves have yet provided a rigorous observational demonstration that a black hole is present in these systems. For the stellar mass cases in particular, the experimental approach most often used is proof by mass determination: if the compact, accreting object exceeds the maximum stable mass of a neutron star, then it must be a black hole. The mass determination is usually made by optical observations of the companion that determine the mass function of the accreting binary system. X-ray observations establish the compact nature of the source. This approach is indirect in that it establishes a black hole by excluding a particular alternative, a stable non-collapsed configuration, rather than by observing some distinctive signature indicative of an event horizon in the system. Excluding alternatives is not quite the same as demonstrating a horizon.

One of the ways that X-ray observations can be used in the study of black holes is to observe strong gravitational field effects associated with the hole that can be isolated in the short timescale X-ray variability of the source. (Another tool is X-ray polarimetry measurements. See R. Stark's contribution in this volume.) For example, the mass and angular momentum of a black hole are two properties that can, in principle, be determined by external measurements. These properties of the hole determine the innermost marginally stable orbit around the hole, which, in turn, sets the inner boundary of the accretion disk. For a known mass, the period of the innermost stable orbit is a function of the magnitude and direction of the angular momentum of the hole. Thus, if we knew the mass and could measure the innermost stable orbit period, the angular momentum of the hole could be determined.

There is some evidence that emission from the inner disk can be isolated. From observations of the rapid X-ray variability from Cygnus X-1, Meekins, *et al.* (1984) found that a substantial fraction of the emission was modulated near a preferred timescale of 3 milliseconds. Order of magnitude considerations show that the timescale and magnitude of these fluctuations require an origin in the inner accretion disk. In addition, a turnover in the variability power was found on timescales shorter than 3 ms. This may signal detection of the inner edge of the disk.

It must be stressed that these results were based not on the detection of single bursts but rather from the study of long strings of data. In other words the bursts are not studied singly but in a statistical aggregate. An XLA class instrument is needed to see individual burst events and measure their temporal profiles and energy

spectra. These observations should lead to a much improved theory of the inner edge of the disk and therefore its use as a probe of the gravitational metric in this region.

In this talk we have stressed two applications of X-ray timing observations with a large area detector. There are many others. In conclusion, we point out that the historical experience in X-ray timing, from the UHURU satellite onward, has been one of continual surprise. EXOSAT (launched 1983) is particularly remembered for the discovery of quasiperiodic oscillations in neutron stars: a phenomenon that was unforeseen when EXOSAT was launched. In the age of the NASA Space Station, it will be possible to construct instruments with 100 m^2 aperture and the commensurate data handling capability that will make possible X-ray timing observations on timescales as short as a few tens of microseconds. These timescales are at least a factor of 1,000 shorter than the shortest accessible with past and current generation satellites and about 10^5 shorter than typical capabilities. This is a largely unknown territory but, based on past experience, we can anticipate many important discoveries.

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DISCUSSION

SCHUTZ: I'd like to reinforce what you said about the relation of this experiment to ground-based gravitational wave detectors. If we could detect Wagoner's accretion-driven unstable neutron stars we would learn a great deal about neutron star structure and the equation of state of neutron matter. But even broad-band laser interferometers may not have sufficient sensitivity to detect the gravitational waves without using narrow-banding techniques to enhance sensitivity at the frequency of the wave. So they will need to know this frequency ahead of time, and XLA can make a big contribution to gravitational wave astronomy.

WOOD: Yes, that's correct. In principle one could use either type of detector, gravitational wave or X-ray, for initial discovery of the continuous-wave signal and then look in the other channel at the frequency that had been discovered. It appears that prospects for initial discovery are far better in X-rays. I should stress that it is important to know not only the frequency of the CFS signal in the center-of-mass frame of the neutron star but also the orbital elements of the binary system, because orbital motion introduces a substantial frequency modulation. The large X-ray aperture overcomes the FM by providing sufficient sensitivity for detection in a small fraction of an orbital period, and once the signal is found, it can be used to work out the necessary orbital elements. The X-ray and gravitational wave observations contribute complementary information about the source.

WEISS: Can you compare XLA with XTE? (The X-ray Timing Explorer).

WOOD: XLA represents the genera and has far greater capability. XLA is 200 times larger and has a maximum telemetry data rate several hundred times greater than that of XTE, both of which are needed for working at higher signal-to-noise on very short timescales. The two experiments operate in the same energy range and can isolate essentially the same set of sources (excepting transients active for one and not the other). XLA can make all the observations that XTE's proportional counter array can make, but it also can carry out other observations that go far beyond XTE's capabilities. These latter observations are the ones that have been discussed here. Being 100 times larger does not make it 100 times as expensive. There should be very significant economies of scale in the manufacture of many proportional counters. Some of the functions of the free-flyer satellite that carries XTE are in the case of XLA provided by the Space Station, for example power and telemetry. The Space Station provides maintenance access as well.

HELLINGS: Can this detector act as a polarimeter in the sense of Richard Stark's suggestion?

WOOD: There is a possibility that polarimetry capability could be incorporated, by measuring the pulse rise time as well as the amplitude for each X-ray event. This approach was examined some years ago and found to be sufficiently sensitive only when there are very large numbers of photons, but that is exactly what the large area of XLA provides. This issue needs to be re-examined in the XLA context. In any X-ray polarimetry it is essential to be able to distinguish real polarization effects from spurious effects of instrumental origin. Laboratory work on that is needed.

SHAPIRO: What sort of angular resolutions do you expect to obtain with your array and how do you plan to achieve them?

WOOD: The basic proportional counter units have mechanical collimators that provide a field of view of 1 square degree. This is sufficient to isolate the bright sources that will be used for the timing work, i.e., the 2000 brightest sources in the sky. It would be straightforward to have a co-aligned monitor imaging detector observing the field simultaneously. (A coded aperture could monitor the field with resolution of a few arcminutes.) We regard this as an option, not absolutely essential, because in those cases where it was desirable to monitor the field of view it might be possible to arrange simultaneous observation with another instrument such as AXAF.

Very high angular resolution for mapping on fine scales is achieved by using XLA in conjunction with a distant occulting edge that moves slowly across the field of view, either a natural occulter (the moon) or an artificial one. The angular resolution achievable varies with the source and observing configuration, but it would be possible to reach milliarcseconds on sources as faint as the brighter quasars and active galactic nuclei. One must be able to see the source at sufficient signal-to-noise in the time the occulter sweeps the angular scale of interest. This is roughly a thousandfold better than the best angular resolution achievable in X-rays by other means.

FAIRBANK: What is the angular resolution if you provide a knife edge with another satellite?

WOOD: There are several reasons to provide an artificial satellite with a smooth edge that can be steered around to provide artificial occultations. The machined edge removes the necessity for knowing the lunar terrain in the region that provides the occultation, which means that the limit on angular resolution with a bright source will be set by diffraction and might become as fine as 100 micro-arcseconds. It is possible to steer the artificial occulter to any point on whole sky, so that there is access to a much larger sample of targets, and the artificial occultations can be scheduled to occur at convenient times.

To get the occulter to move slowly enough it must be at roughly the distance of the moon. The technical problems involved in realizing precision navigation of a satellite in such a high orbit are (i) minimizing the control impulse (propellant) required for navigation and (ii) the error budget, that is, determining what correction to apply to achieve occultation. A study done by NRL and Stanford showed that both problems could be solved by placing the satellite in an orbit perpendicular to the lunar orbit and suitably phased so that the gravitational pull of the moon advances the orbit plane without fuel expenditure. Control impulse is applied only to in-track maneuvering.